Chiral symmetry and baryon masses in the 2+1 flavour Nambu-Jona Lasinio model

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Introduction

It is beyond any reasonable doubt that quantam chromodynamics (QCD) is the theory of strong interactions. The final goal of QCD is to classify all the hadronic phenomena in terms of the fundamental constituents of baryons and mesons called quarks and gluons. For very high energy processes such as the deep inelastic lepton—hadron scattering (DIS), QCD has shown remarkable success, which is due its asymptotic-free nature . On the other hand, at low energies comparable to the low lying hadron masses ($\sim$ 1 GeV), QCD shows non-pertubative behaviour such as the confinement of quarks and gluons and the dynamical breaking of chiral symmetry, which make the analytic study of QCD very difficult.The difficulties involved in obtaining low-energy properties directly from QCD, have motivated the construction of effective models. One such effective model is Nambu Jona-Lasinio model that entails chiral symmetry breaking in quarks at low density and temperature, and chiral symmetry restoration in quarks at high density and temperature. Further, LQCD as well as other effective model calculations at finite temperature shows that this symmetry is restored above so called chiral transition temperature (T_c) above which masses of approximate Goldstone modes drops down to current quark mass. The masses of these (approximate) Goldstone modes show a weak dependence on the temperature as these are related to approximate SU(3) chiral symmetry breaking as such taken constant in most explicit model computations. This study as such focuses on calculating only baryon masses, which consist of quarks whose constituent mass depends on both temperature (T) and chemical potential (μ) which in turn makes the baryon masses T and μ dependent [1, 2, 3].

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Formalism

The basic and most widely used 2+1 flavour NJL langrangian is [1, 4] :

$$\mathcal{L}_{\rm NJL} = \bar{q}(i\partial\!\!\!/ - \hat{m})q + \frac{g_S}{2}\sum_{a=0}^{8}\left[(\bar{q}\lambda^a q)^2 + (\bar{q}i\gamma_5\lambda^a q)^2\right] - g_D\left[\det\bar{q}(1+\gamma_5)q + \det\bar{q}(1-\gamma_5)q\right] \quad (1)$$

Here q=(u,d,s) is the quark triplet,$\hat{m}$=(m_{0u}, m_{0d}, m_{0s}) is the current quark mass matrix which explicitly breaks SU(3) chiral symmetry .λ^a are Gell-Mann matrices. The determinant term is chiral invariant but breaks $U_A(1)$ symmetry and is reflection of axial annomaly in QCD. . Using the Hartee fork approximation one can effectively obtain the gap equation for the constituent quark masses as:

$$m_i^* = m_{0i} - 4G_s < \overline{\psi}_i\psi_i > -2K_s < \overline{\psi}_j\psi_j >< \overline{\psi}_k\psi_k > .. \quad (2)$$

where i,j,k=u,d,s quark and $i \neq j \neq k$, G_s and K_s are coupling constants and $< \bar{\psi}_i\psi_i >$ is quark condensate given by:

$$\alpha_i = -\frac{2N_c}{2\pi^3}\int_0^\Lambda \frac{m_i^* d^3p}{E_i}[1 - f_i(T,\mu) - \overline{f}_i(T,\mu)] \quad (3)$$

The gap equations are substituted in the following constituent mass formula to obtain baryon masses:

$$M_B^* = M_0 + \sum_i^{u,d,s}\left(M_i + \frac{a}{2M_i}\right) + b\sum_{i<j}\frac{\sigma_i\sigma_j}{M_iM_j} \quad (4)$$

Here M_0 represents the contributions of the confinement potential and the short-range color—electric interaction, which are independent of the constituent masses. $a/2M$ denotes the kinetic energy of the confined quarks. The spin—spin term with the coefficient b is the color—magnetic interaction responsible for the octet—decuplet mass splitting [4].

Results and Conclusion

We use the parameter set of Ref.[4] to compute the masses of constituent quarks.Here we assume iso-spin symmetry of two light quarks i.e $m_{0u} = m_{0d} = 5.5$ MeV. Fig.1 shows constituent quark mass as a function of temperature. From the fig. it is clear that $m^*_{u,d}$ decreases with T and drops approximately to current quark mass at around 0.2 GeV. Albeit the strange quark mass (M_s) also decreases with T, it does not attain its current mass [3] .

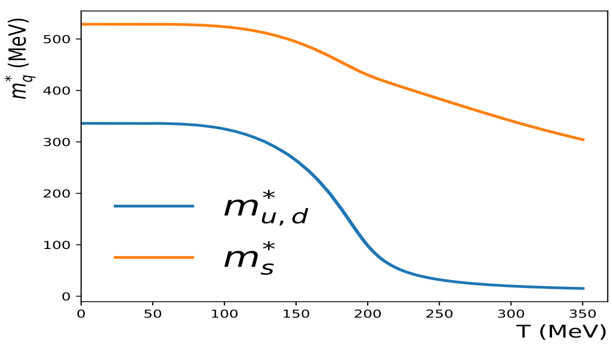

Figure 1: The graph shows the variation of constituent quark masses m^*_q as a function of temperature.

The temperature at which constituent quark masses attains its current quark mass is called transition temperature (T_c) corresponding to chiral restoration phase transition. While the quark condensate for u quark starts abruptly decreasing near the phase transition for s-quark,the quark condensate does not decrease too much even after the transition temperature is attained ,indicating strong interaction among s-quarks. Owing to the non-zero current quark masses chiral symmetry as such is only an approximate symmetry in QCD. So in view of Ginzburg-Landau theory, the quark condensate can become a true order parameter only when quark masses are in chiral limit $m_{i,j,k} = 0$. Although the $\bar{s}s$ content is smaller than $\bar{u}u$ or $\bar{d}d$ in the nucleon, it is not negligible. Furthermore,the non-strange content of Ω^- is even larger than the strangeness content of the proton. This is simply because the u(d)-quark has a mass (current and constituent) smaller than that of the

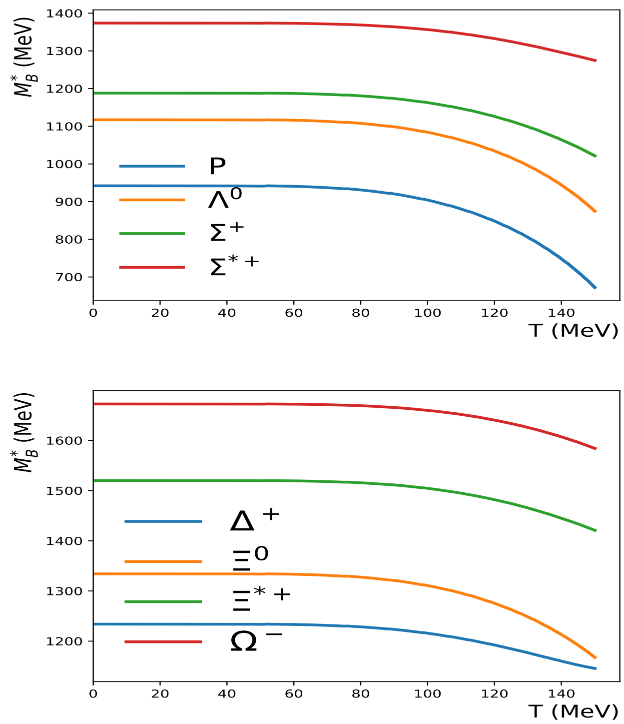

Figure 2: The graph shows the variation of baryon masses with temperature at $\mu = 0$.

s-quark, hence gets easily excited [4] . From the Figs. 3 and 4 it is clear that though the baryon masses do not change significantly upto the temperature of 100 MeV but above it they start decreasing significantly. This decrease in baryon masses with increasing temperature is significant mostly in baryons which are made up of u and d quarks compared to baryons which are made up of strange quarks owing to the strong interaction among s-quarks.

References

[1] S. P. Klevansky, *Reviews of Modern Physics*, **64**(3), 649 (1992)

[2] S. A. Mir et al. [arXiv:2406.11752[hep-ph]]

[3] G. P. Kadam, *Eur. Phys. J. A* **53**, 13 (2017).

[4] T. Hatsuda and T. Kunihiro, *Phys. Rept.*, vol. 247, pp. 221–367, 1994.